# Emergency Communications for NASA's Deep Space Missions

by

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# Background

- Emergency communications services offered by the Deep Space Network (DSN) are not used very often but practically all deep space have used the service.
- Emergency communications is characterized by limited or no pointing capability by the spacecraft.
  - Requires broad-beam Low Gain Antennas (LGAs) or Medium Gain Antennas (MGAs).
  - Cannot use long block length channel codes because the spacecraft may be tumbling. Smaller block length channel codes and convolutional codes have lower coding gains than longer block length codes.
- Emergency could occur at any time so the link has to be very reliable.
  - Requires more energy per bit.
- Because we cannot use High Gain Antennas (HGA) and codes with large coding gains, and because we have to use more energy per bit, the data rate for emergency mode communications is much lower than nominal science operations.

## Questions to Answer

- Given the DSN assets at what distance can we uplink to a spacecraft during an emergency?
  - Over an omni-directional antenna (0-dB gain).
  - Over an LGA or an MGA directional antenna (gain>0 dB).
- Given the DSN assets and a distance, how much power does the spacecraft need to communicate with Earth?
  - Over an omni-directional antenna.
  - Over an LGA or an MGA.
- Note: Solar powered spacecraft require some pointing capability in order keep the spacecraft powered. This same pointing capability could be used to point directional LGAs/MGAs at least towards the sun.

# GENERAL ASSUMPTIONS

# Assumptions: General Link Operations

- Both uplink and downlink operate at Canberra DSN Communications Complex at 20 degrees elevation with 99% weather (1% outage due to the weather) at10 bps.
- Residual Carrier BPSK.
  - Requires 11 dB carrier loop SNR to lock the carrier. Synchronization losses ~0.5 dB.

## Assumptions: Spacecraft

- The directional LGA/MGA antennas are circular (either horn or parabolic) and have a Gaussian beam pattern with 50% efficiency.
- We ignore solar scintillation effects during superior solar conjunction.
- We ignore increase in the spacecraft SNT when the spacecraft antenna is sun-pointed.

# Assumptions: Ground Assets

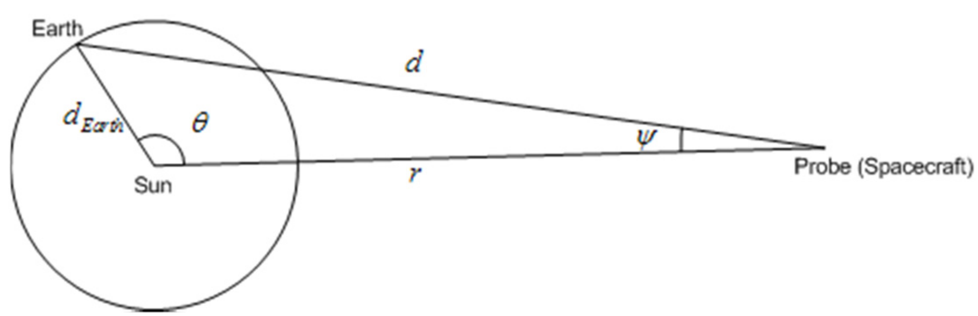
| Ground Asset | Uplink EIRP (dB-W) | Downlink G/T (dB-$K^{-1}$) |
|---|---|---|
| 34-m BWG, 20-KW Transmitter[1]. | 109.5 | 51.5 |
| 34-m BWG, 80-KW Transmitter[1] | 115.6 | 51.5 |
| 70-m, 20-KW Transmitter | 115.7 | 58.0 |
| 70-m, 80-KW Transmitter[2] | 121.7 | 58.0 |
| 70-m, 500-KW Transmitter[2] | 129.7 | 58.0 |

1. 34-m antennas could be arrayed for uplink and downlink. Arrayed antennas improve performance by a factor of $n$ for downlink and $n^2$ for uplink. A 1 dB arraying loss is assumed for both uplink and downlink analysis.
2. 80-KW and 500-KW X-band transmitters are not slated for implementation at the DSN and are only used for hypothetical analysis.

# SELECTION OF LGA/MGA ANTENNA SIZE

## Optimum LGA/MGA Selection for Sun-pointed Spacecraft (1/4)

- A signal to or from a sun pointed spacecraft in the plane of ecliptic outside of Earth's orbit around the sun is multiplied by the space loss and the off-boresight gain of the antenna.
  - We can calculate the off-boresight gain of the antenna from the antenna diameter (*D)* for circular antennas (either horn or parabolic).
  - We can calculate the space loss from the geometry: Earth-Sun-Probe (ESP) angle $\theta$ and spacecraft-sun distance, *r*.
  - The total path attenuation factor could be presented as $\gamma(D,\theta,r)$



## Optimum LGA/MGA Selection for Sun-pointed Spacecraft (2/4)

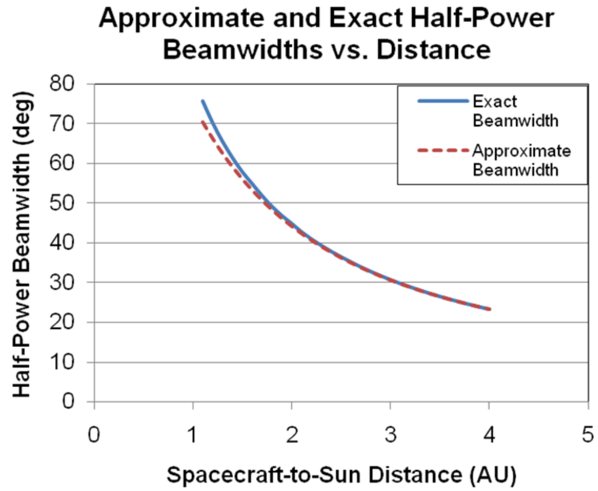
- Selection of the optimum LGA/MGA antenna size for a spacecraft operating at distance $r$ from the sun is a max/min problem.

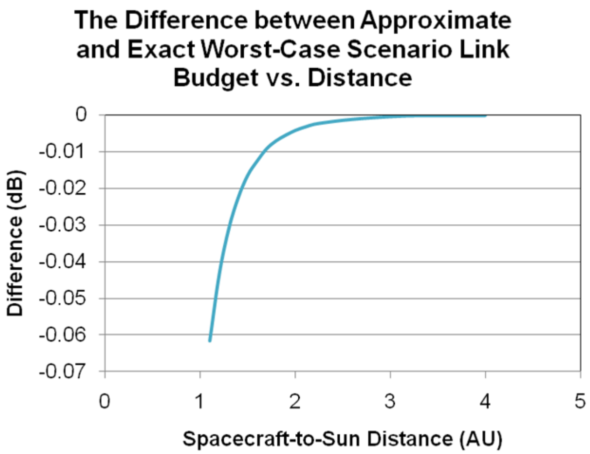
$$D_{opt}(r) = \max_{D}\left[\min_{\theta} \gamma(D, \theta, r)\right]$$

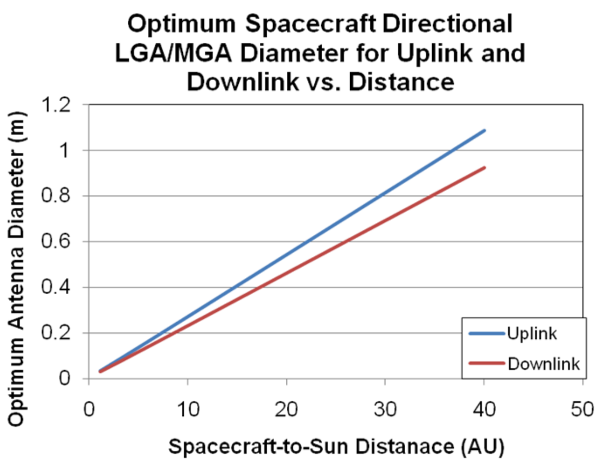
## Optimum LGA/MGA Selection for Sun-pointed Spacecraft (3/4)

- For any spacecraft-sun distance *r*> 1 AU, the optimum antenna can be selected such that for an ESP=90 deg., the antenna has a boresight loss of 4.34 dB. Incidentally, for such an antenna, the worse case path attenuation occurs when ESP=~90 deg.
  - Approximation is tight and the link performance calculations differences between approximate and exact calculations vanish as *r* (spacecraft-sun distance) becomes large.
- For large *r*, the optimum antenna diameter become proportional to *r* and the performance at the worst case angle (ESP=90) becomes independent of *r*.
  - Implies that the uplink margin and the required downlink power will be constant and independent of *r* for sun-pointing spacecraft with optimum directional antennas.
- NOTE: Analysis valid only for missions outside of Earth's orbit around the sun.

# Optimum LGA/MGA Selection for Sun-pointed Spacecraft (4/4)



# UPLINK ANALYSIS

## Uplink Analysis: Assumptions (1/7)

- 7.17-GHz "X"-band frequency.
- The link operates with a positive margin.
- (63, 56) BCH channel code operating at $E_b/N_0$ of 10 dB.
  - BER of $10^{-8}$, undetected BER of $10^{-10}$, needed to assure no errors in uplink commands.
- Spacecraft Carrier Loop Bandwidth: 100 Hz.
- Spacecraft System Noise Temperature: 400 K.

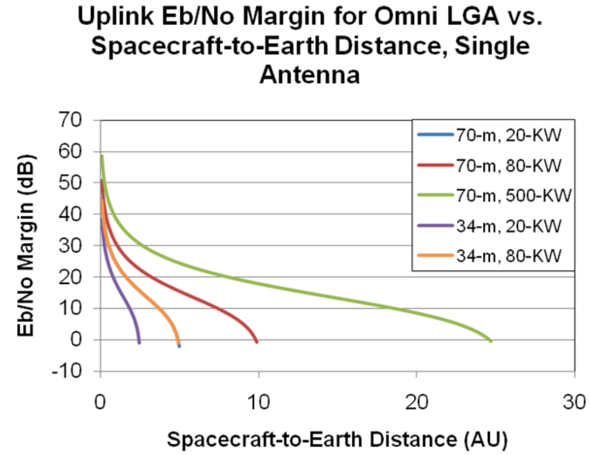
## Uplink Analysis (2/7)

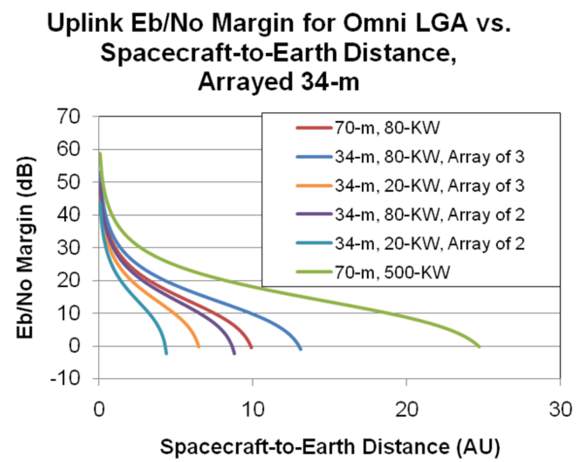
- Calculate the $E_b/N_0$ margin at the spacecraft by selecting the mod index such that the carrier loop SNR at the spacecraft is 11 dB and the rest of the power is given to data.
  - For omni-directional antenna calculate the margin as a function of spacecraft-Earth distance.
  - For directional LGA/MGA calculate the margin as a function of spacecraft-sun distance.

# Uplink Analysis: Omni Performance (3/7)

**Maximum Distance for Uplink Communications through an Omni for Different Uplink Assets Configurations.**

| Uplink Assets Configuration | Maximum S/C-Earth Distance (AU) |
|---|---|
| Single 34-m, 20-KW | 2.4 |
| Two 34-m, 20-KW | 4.3 |
| Single 34-m, 80-KW | 4.8 |
| 70-m, 20-KW | 4.9 |
| Three 34-m, 20-KW | 6.4 |
| Two 34-m, 80-KW | 8.6 |
| 70-m, 80-KW | 9.9 |
| Three 34-m, 80-KW | 12.9 |
| 70-m, 500-KW | 24.6 |

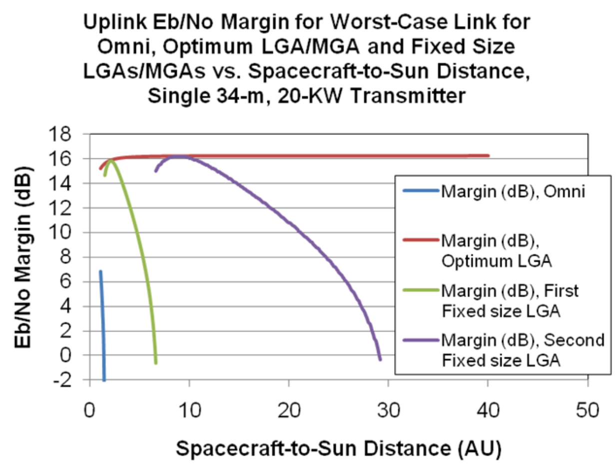


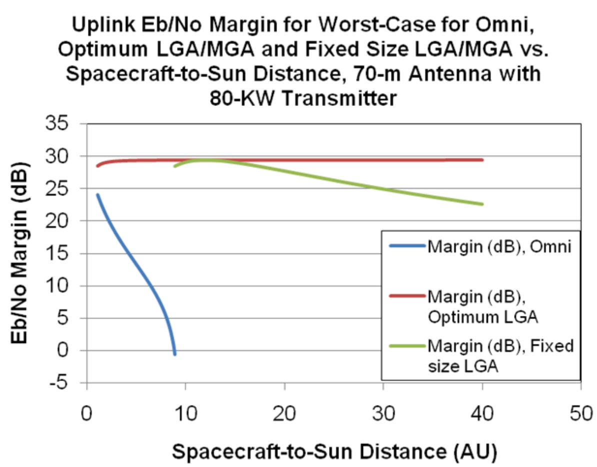



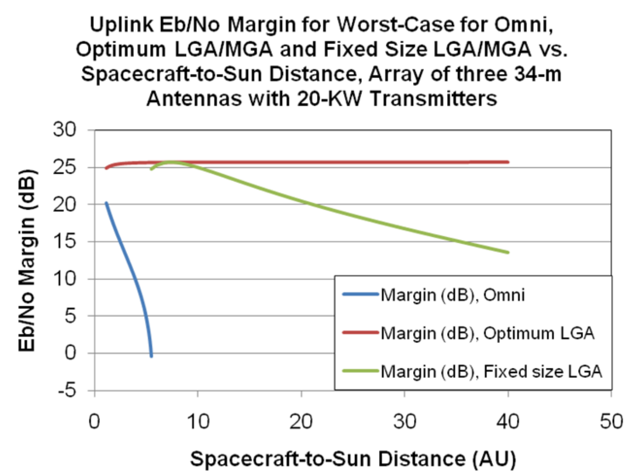
# Uplink Analysis (4/7)

- Look at the link margin as a function of distance for a optimum sized LGA/MGA.
- Evaluate the utility of a suboptimal directional LGA/MGAs of fixed sizes for deep space missions.
  - Strategy: Use the omni directional antenna until the uplink margin falls below zero for the worse case link (with omni this is ESP=180) and use a directional antenna whose 90 deg. ESP off-boresight loss when sun pointed at the given distance is 8 dB. Switch to another directional antenna when the margin for the first directional antenna falls below zero for the link's worse ESP angle as distance increases (note as the distance increases, the worst ESP angle is 180 degrees for any fixed size antenna).

# Uplink Analysis (5/7)



# Uplink Analysis (6/7)

**Maximum Distance for Uplink Communications through a Fixed-Size, Suboptimal, LGA/MGA for Different Uplink Assets Configurations and LGA/MGA Diameter and Half-Power Beamwidth**

| Uplink Assets | Max S/C-Sun Distance (AU) | LGA/MGA Diameter (m) | Half-power Beamwidth (deg.) |
|---|---|---|---|
| Single 34-m, 20-KW, 1st LGA/MGA | 6.5 | 0.059 | 44.2 |
| Single 34-m, 20-KW, 2nd LGA./MGA | 29 | 0.238 | 10.9 |
| Two 34-m, 20-KW | 27.3 | 0.124 | 21.0 |
| Single 34-m, 80-KW | 34.4 | 0.138 | 18.9 |
| 70-m, 20-KW | 36.8 | 0.145 | 17.9 |
| Three 34-m, 20-KW | >40 | 0.198 | 13.1 |
| Two 34-m, 80-KW | >40 | 0.278 | 9.35 |
| 70-m, 80-KW | >40 | 0.321 | 8.09 |
| Three 34-m, 80-KW | >40 | 0.433 | 5.99 |
| 70-m, 500-KW | >40 | 0.857 | 3.03 |

## Uplink Analysis (7/7)

- The uplink reach over an omni is limited and only a 70-m with 500 KW transmit power can reach beyond 15 AU.
- Current single antennas have a reach of less than 5 AU.
- Margin for optimum LGA/MGA becomes constant as Space-to-Sun distance increases.
- Combination of omni and a suboptimal LGA/MGA for a sun-pointing spacecraft can provide adequate uplink coverage for spacecraft.

# DOWNLINK ANALYSIS

## Downlink Analysis: Assumptions (1/3)

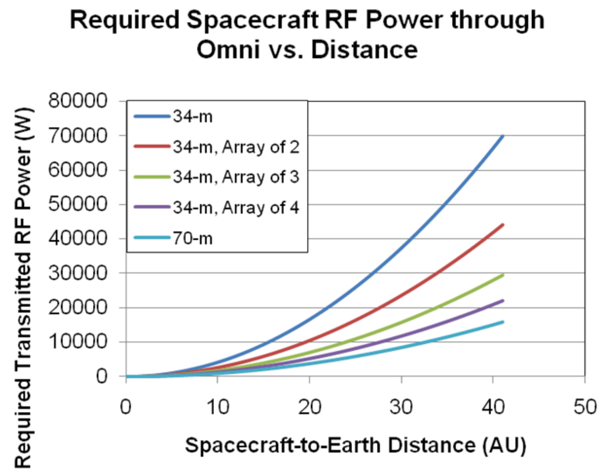
- 8.42-GHz X-band frequency.
- (7,1/2) Convolutional Code with $E_b/N_0$ of 4.12 dB.
  - BER of $10^{-5}$
- Carrier Loop Bandwidth of 10 Hz.
  - Wide loop bandwidth for possible use of auxiliary oscillator.
- For Proper operations, the ground need to have a received $P_t/N_0$ of 21.9 dB-Hz.

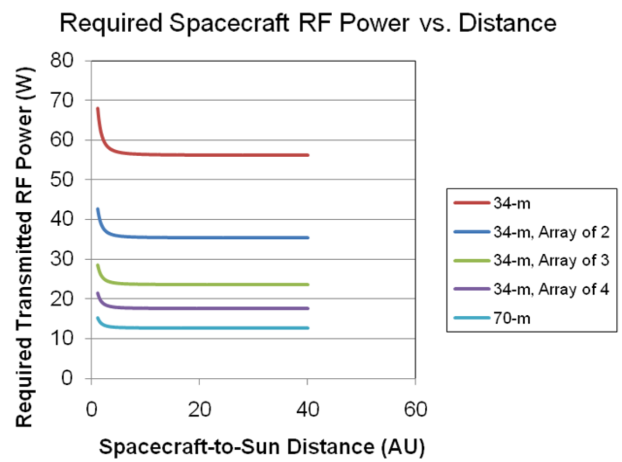
## Downlink Analysis (2/3)

- For downlink we calculate the necessary transmitted power on the spacecraft so that the link will have a $P_t/N_0$ of 21.9 dB-Hz.
  - Results for omni antennas as a function of Spacecraft-Earth distance.
  - Rresults for optimum directional LGAs/MGAs for sun-pointing spacecraft as a function of Spacecraft-Sun distance.

# Downlink Analysis (3/3)

- Downlink power through omni prohibitive.
- Downlink power through optimum LGA/MGA reasonable.
- Directional LGA/MGA necessary for downlink emergency communications.



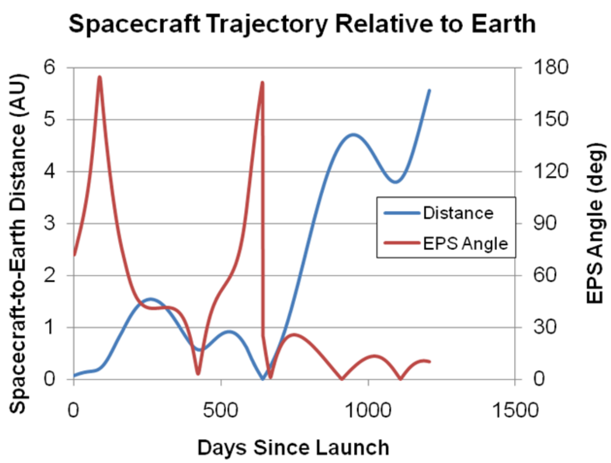
# CASE STUDY: SATURN

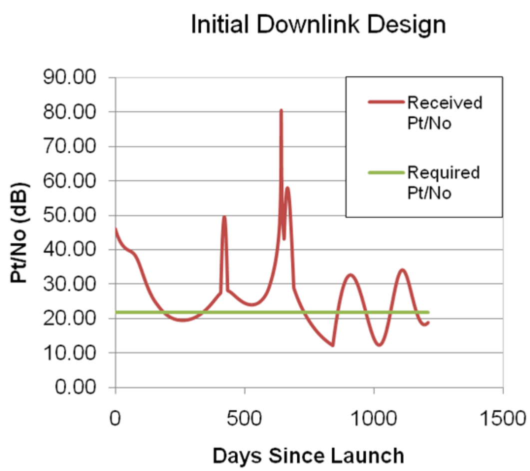
# Case Study (1/2)

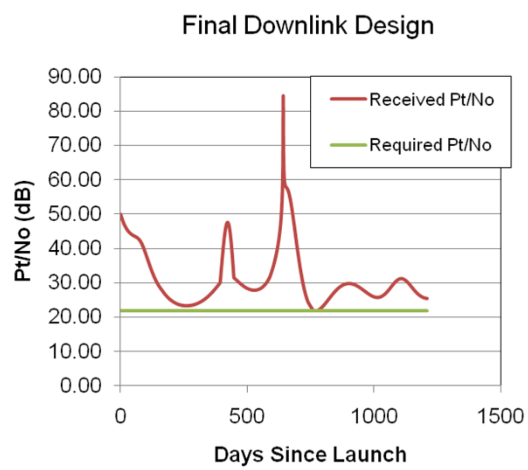
- Optimum LGA/MGA is good at destinations but the emergency system has to operate through the entire duration of the mission including the cruise phase.
- Approach:
  - Given the ground assets used selected for the emergency support of the spacecraft, select the optimum antenna size and power for destination first and see if it has positive margin during the cruise using spacecraft trajectory. If it does then done.
  - If the initial design fails to have a positive margin any time during the cruise, then increase the transmitted spacecraft power and broaden the antenna beam until the design meets requirements both during the cruise and at the destination.
  - Note: focus is on the downlink because required spacecraft power is much more sensitive to LGA/MGA selection.
- Assumption: the spacecraft will use omni antenna for emergency when the off-boresight loss for the directional antenna is greater than 8 dB.

# Case Studies: Saturn

- Required to communicate with a 70-m antenna
- Initial Design:
  - 10.24 deg. HPBW, 22 cm in diameter and 12.6 W transmitted power.
- Final Design:
  - 22.32 deg. HPBW, 10 cm in diameter and 31.1 W transmitted RF power.



# Conclusions

- Practically all planetary missions need directional LGA/MGAs for their emergency communications from the spacecraft to Earth.
- The current uplink capability of the DSN through omni directional antennas is limited.
- Analysis provides method for designing the emergency mode communications over the entire mission for spacecraft operating outside of Earth's orbit around the sun.

# Caveats and Future Work

- Analysis is theoretical and should be used as a first cut for designing emergency telecom.
- No consideration given to emergency com for missions outside of the ecliptic or to missions to Venus and Mercury.
- No consideration of maneuvers during which the spacecraft emergency telecom has to be used (orbit insertions and trajectory correction maneuvers).
- 99% weather availability may be too low and additional margin may be required by missions.
- Ignores increase in spacecraft SNT for sun-pointed spacecraft.
- Need to consider actual LGA/MGA antenna patterns instead of theoretical Gaussian patterns.
- Need to look at advanced channel coding for uplink and downlink to see how much the performance varies.
- Need to look at operational experience of NASA missions.